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In Situ Measurements of Nitrate Leaching Implicate Poor Nitrogen and Irrigation Management on Sandy Soils

R. J. Gehl, J. P. Schmidt,* L. R. Stone, A. J. Schlegel, and G. A. Clark

ABSTRACT

Minimizing the risk of nitrate contamination along the waterways of the U.S. Great Plains is essential to continued irrigated corn production and quality water supplies. The objectives of this study were to quantify nitrate (NO_3) leaching for irrigated sandy soils (Pratt loamy fine sand [sandy, mixed, mesic Lamellic Haplustalfs]) and to evaluate the effects of N fertilizer and irrigation management strategies on NO_3 leaching in irrigated corn. Two irrigation schedules (1.0× and 1.25× optimum) were combined with six N fertilizer treatments broadcast as NH_4NO_3 (kg N ha^{-1}): 300 and 250 applied pre-plant; 250 applied pre-plant and sidedress; 185 applied pre-plant and sidedress; 125 applied pre-plant and sidedress; and 0. Porous-cup tensiometers and solution samplers were installed in each of the four highest N treatments. Soil solution samples were collected during the 2001 and 2002 growing seasons. Maximum corn grain yield was achieved with 125 or 185 kg N ha^{-1}, regardless of the irrigation schedule (IS). The 1.25× IS exacerbated the amount of NO_3 leached below the 152-cm depth in the preplant N treatments, with a mean of 146 kg N ha^{-1} for the 250 and 300 kg N preplant applications compared with 12 kg N ha^{-1} for the same N treatments and 1.0× IS. With 185 kg N ha^{-1}, the 1.25× IS treatment resulted in 74 kg N ha^{-1} leached compared with 10 kg N ha^{-1} for the 1.0× IS. Appropriate irrigation scheduling and N fertilizer rates are essential to improving N management practices on these sandy soils.

Nearly half of the U.S. population relies on ground water as a source for drinking water (USEPA, 1987); in Kansas, 70% of the total population and 85% of the rural population depend on ground water for their drinking water supply (Townsend and Young, 2000). Nitrate is one of the most widespread ground water pollutants, and drinking water with a large NO_3 concentration may induce negative health effects, such as birth defects, cancer, nervous system impairments, and methemoglobinemia (Keeney, 1987; Jemison and Fox, 1994). Once introduced to the ground water, NO_3 is difficult to remove and may cause water quality problems for a prolonged period of time (Altman and Parizek, 1995). Nitrate contamination of ground water has become an important environmental issue throughout the United States and especially in the Great Plains region.

Nitrate concentrations are frequently in excess of natural background levels (3.0 mg L^{-1}) in the Central High Plains and Great Bend Prairie Aquifers—important water resources to south-central Kansas (Townsend and Young, 1995; Pope et al., 2001). Recent reports by the Kansas Department of Agriculture (Emmons, 2000) and the United States Geological Survey (Pope et al., 2001) have identified as many as 15% of ground water wells with NO_3–N concentration exceeding 10 mg L^{-1}, the USEPA Maximum Containment Level (MCL) for drinking water quality. Pope et al. (2001) reported NO_3 enrichment in water for 80% of the sampled wells in a study that included counties along the Arkansas River between Edwards and Reno County, KS. In another study of Kansas farmstead wells, Steichen et al. (1988) reported that 28% of sampled wells exceeded the MCL for ground water NO_3.

Irrigated agriculture is implicated as a contributor to NO_3 contamination of surface and ground water in many corn (*Zea mays* L.) production regions, including the central Great Plains (Ferguson et al., 1991; Schepers et al., 1991; Burkart and James, 1999; Sogbedji et al., 2000). The coarse-textured soils common to this region have a low capacity to hold water and nutrients. Thus, these soils require large inputs of fertilizer and irrigation for optimum crop production, increasing NO_3 movement through the soil profile and loss by leaching (Lembke and Thorne, 1980).

Management practices to reduce NO_3 loss must be tested to provide a measurable benefit to the environment and to producers. Often, indirect evidence implicates N fertilizer use as the source for increased ground water NO_3 concentration, yet research providing direct evidence of this correlation is lacking in many instances.

Quantification of NO_3 leaching to below the corn root zone (about 1.4 m; Leonard and Martin, 1963) is needed to determine the contribution of agricultural practices to NO_3 contamination of ground water (Hergert, 1986). However, direct measurement of solute flux from the vadose zone is difficult and results have been variable (Barcelona and Morrison, 1988). Various methods have been used to collect soil water samples from the unsaturated zone: profile soil sampling (Roth and Fox, 1990; Liang et al., 1991), tile drains (Kladivko et al., 1991; Randall et al., 1997; Sogbedji et al., 2000), drainage from watersheds (Gburek et al., 1986; Lowrance, 1992), ground water wells (Weil et al., 1990; Cambardella et al., 1999), pan lysimeters (Russell and Ewel, 1985; Jemison and Fox, 1994; Toth and Fox, 1998), monolith lysim-

R.J. Gehl, L.R. Stone, and A.J. Schlegel, Department of Agronomy, Kansas State University, 2004 Throckmorton Plant Sciences Center, Manhattan, KS 66506. J.P. Schmidt, USDA-ARS, Building 3702, Curtin Road, University Park, PA 16802. G.A. Clark, Department of Biological and Agricultural Engineering, Kansas State University, 147 Seaton Hall, Manhattan, KS 66506. Contribution no. 05-205-J of the Kansas Agricultural Experiment Station; research supported by the Kansas Department of Agriculture and Fertilizer Check-Off Funds. Trade or manufacturers' names mentioned in the paper are for information only and do not constitute endorsement, recommendation, or exclusion by the USDA-ARS. Received 8 Feb. 2005. *Corresponding author (john.schmidt@ars.usda.gov).

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Abbreviations: ET, evapotranspiration; IS, irrigation schedule or irrigation treatment.

eters (Owens, 1987), and porous cup samplers (Gerwing et al., 1979; Andraski et al., 2000). Litaor (1988) provided a critical review of many of these methods, which all have advantages and disadvantages in applied situations. But no single and simple method exists for soil solution sampling under most soil conditions.

Darusman et al. (1997a, 1997b) used data from tensiometers in conjunction with predetermined hydraulic conductivity vs. matric potential relationships and Darcy's law to estimate soil water drainage in two Kansas soils. Normand et al. (1997) used porous suction cup samplers with a continual measurement of soil water balance using a neutron moisture meter and tensiometers to determine NO_3 transport in a sandy-textured irrigated corn field. Similarly, Paramasivam et al. (2001) estimated NO_3 leaching losses by measuring soil water NO_3 using porous suction cup samplers, combined with a drainage estimate determined using tensiometric data and Darcy's law. The mass of N leached below the root zone in their study was calculated as the product of the mean NO_3 concentration in the leachate sample multiplied by the volume of drainage water in a given time period. The use of tensiometric estimates for the computation of water flux is limited by the variability in soil-water potential at the field scale (Livingston, 1993), although research by Yeh et al. (1986) showed that variation in soil-water pressures is spatially correlated and that variability is mean-dependent (variability tended to increase with a decrease in mean soil-water pressure). Their research suggests that measurements within a plot, though spatially variable, should provide some correlation to soil water status surrounding the point of measurement, and multiple measurements recorded in close proximity can provide a gauge of field soil-water pressure. Their findings further indicate that with relatively moist field conditions (when most drainage occurs) variability in soil matric potential should be minimal. Although spatial variability in leaching characteristics and soil water NO_3 concentrations pose a limitation on the method used by Normand et al. (1997) and Paramasivam et al. (2000), their technique provides a practical means to measuring soil water NO_3 combined with a relatively low-cost estimate of water flux. In addition, the combination of Darcy's law estimates of drainage and estimates of solute concentration from porous cup samplers allows for a quantification of NO_3 leaching with minimal disturbance to the soil and is practical for use in studies with multiple replications and sites. This technique has recently been implemented at several locations in Kansas to evaluate the impacts of irrigated corn production on NO_3 loss to ground water (Heitman, 2003; Wetter, 2004).

The effects of crop, fertilizer, and irrigation management systems on soil NO_3 leaching, determined using various methods, have been evaluated and implemented in the recent past. However, little information is available on field-measured quantification of NO_3 leaching losses from the sandy, irrigated cropland in the Great Plains region. The objectives of this study were to (i) quantify NO_3 leaching for the irrigated sandy soils along Kansas' waterways by using Darcy's law drainage estimates together with measurements of soil water NO_3 concentration, and (ii) evaluate the effects of N fertilizer and irrigation management strategies on NO_3 leaching in irrigated corn.

MATERIALS AND METHODS

This study was conducted in south-central Kansas during 2001 and 2002 along the Arkansas River in Stafford County (98°37′18″ W, 38°15′01″ N; Fig. 1). The site was sprinkler-irrigated. Soils at the site were Pratt loamy fine sands with about 12 g kg^{-1} organic matter, 16 mg kg^{-1} Bray-1 P, 53 mg kg^{-1} K, and pH of 6.1. The site was managed by the cooperating producer as part of the entire field, with the exception of N application and grain harvest. Tillage at the site included chisel plow and a seedbed preparation pass, and weed control included pre-emergence herbicides. The plot area was planted to a full-season corn variety on 1 May 2001 and 5 May 2002.

A randomized complete block design (RCBD) with four replications of six N treatments was used at the site. Plot dimensions were 6 m (eight rows, 0.76-m row width) wide and 9.1 m long. Nitrogen treatments were surface broadcast-applied as NH_4NO_3 either within 5 d of planting or as a split application with part applied within 5 d of planting and the remainder applied as sidedress applications. Nitrogen treatments included 300, 250, 250 (split), 185 (split), 125 (split), and 0 kg N ha^{-1}. The split applications were divided in 125 and 125; 60 and 125; and 25, 50, and 50 kg N ha^{-1} allotments for the 250, 185, and 125 kg N ha^{-1} treatments, respectively. The first sidedress application was applied at the V6–V8 growth stage (18 June 2001, 13 June 2002; vegetative leaf stage is defined according to the number of leaves having a visible leaf collar, including the first short rounded-tip leaf); the second sidedress application (for the 125 kg N ha^{-1} treatment) was applied at the V10 growth stage (26 June 2001, 11 July 2002). There were two irrigation treatments at the site (optimal water rate [1.0×] and 25% greater than optimal water rate [1.25×]), each of which included a RCBD with the described N treatments (Fig. 2). The greater water rate was achieved by changing nozzles within one span of the irrigation system. The optimal water rate for the Ellinwood site was determined using a water balance irrigation scheduling program (KanSched) (Rogers et al., 2002). Geographic plot locations were identical between years.

Soil profile samples were collected within 5 d of planting (preplant) and before N fertilizer applications; and post-harvest to a 240-cm depth in 30-cm increments. One core (5-cm i.d.) from within the row and one core from between the rows were collected from each plot using a hydraulic soil probe and

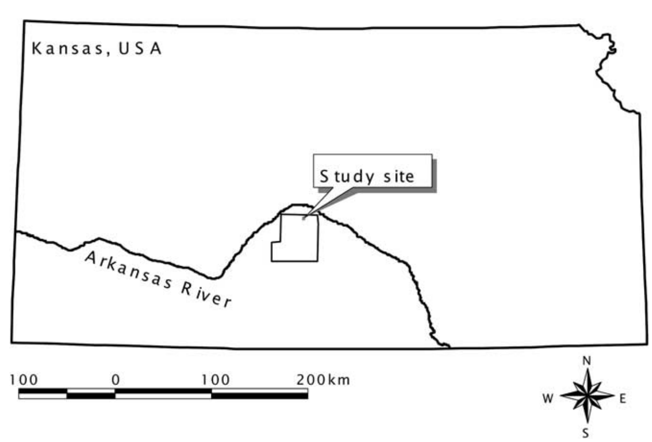

Fig. 1. Map of Kansas, USA, with the study site identified in Stafford County.

then combined for analysis. Subsamples (about 300 g each) of the preplant and post-harvest samples were collected at the time of sampling for determination of gravimetric water content using the oven-drying procedure described by Gardner (1986).

Soil samples were collected in May 2003 to determine dry bulk density according to the method of Blake and Hartge (1986). Five cores (6.7-cm i.d.) were collected from the entire plot area to a depth of 240 cm in 30-cm increments using a hydraulic soil probe. Samples were dried at 105°C for 2 d and dry soil weight recorded. Mean dry bulk density (g cm^{-3}) was determined by averaging across all cores for each depth.

Samples collected for dry bulk density were also used for textural analysis by the hydrometer method (Gee and Bauder, 1986), with sodium hexametaphosphate as the dispersing agent. Textural analysis was completed to a depth of 240 cm in 30-cm depth increments. Clay fraction was determined by reading an ASTM no. 152H standard hydrometer with a Bouyoucos scale (g L^{-1}) after 8 h of settling. Sand fraction was determined by separation with a 20-cm-i.d., 53-μm sieve. Sand particles were not further fractionated. Silt content was determined by subtracting the clay and sand fractions (g g^{-1}) from 1.

Porous-cup solution samplers (1 per plot) and tensiometers (3 per plot) were installed within the row (center rows within a plot) in all replications of the four highest N treatments in late May of each year. Solution samplers were installed at the 152-cm depth; tensiometers were installed at depths of 30, 137, and 168 cm. Tensiometer design was similar to that shown by Young and Sisson (2002, Fig. 3.2.2–4) and is described in detail by Gehl (2004). Bodies of the tensiometers were constructed of poly-vinyl chloride (PVC) tubing fitted on one end with a porous ceramic cup (0655X01-B1M1; Soilmoisture Equipment Corp., Santa Barbara, CA). During the growing season, de-aired water was added to the tensiometers to maintain the internal water level as dictated by field conditions.

Solution samplers were constructed similar to the tensiometers and as described by Linden (1977). One end of the PVC sampler body was fitted with a porous ceramic cup (0655X01-B1M3; Soilmoisture Equipment Corp.). Each sampler was connected through a series network of high density tubing to other samplers and ultimately to a vacuum source. For sample collection, a constant vacuum of 68 kPa was applied to the networked samplers for at least 3 h using two vacuum pumps. The entire solution volume was removed from the samplers during each collection. Soil solution remaining within the pores of the ceramic material after sample evacuation was not removed and discarded due to the restrictiveness imposed by the experimental setup and the relatively dry soil environment. Sample volume varied depending on soil moisture, but typically ranged between 10 and 60 mL. All plot instrumentation was removed in late September of each year, before field harvest.

Tensiometer readings were taken about every 7 d from May through August in 2001 and 2002. Solution samples were collected at about 14-d intervals during the same timeframe. Sampling frequency was consistent with that of similar research studies (Hergert, 1986; Heitman, 2003) and was sufficient for revealing trends in water flux and NO_3 leaching. Solution samples were stored at 4°C before analysis for NO_3–N (as NO_2–N and NO_3–N, hereafter reported as NO_3–N) and NH_4–N, which was completed within 48 h of collection following RFA Methodology no. A303-S170 (Alpkem Corporation, 1986b) and A303-S021 (Alpkem Corporation, 1986a).

The quantity of NO_3 leached below the root zone was estimated using the concentration of NO_3–N in the soil solution collected in the porous cup samplers (152-cm depth) and drainage estimates determined from tensiometric data. Soil water matric potential, h (cm of water), in each plot was determined using data from the 137- and 168-cm tensiometers. Hydraulic head, H (cm), was calculated as the sum of h and gravitational potential head, H_g (cm) (Young and Sisson, 2002):

$$H = h + H_g \quad [1]$$

where H_g was determined using a reference level of the 168-cm soil depth. The hydraulic head gradient $\Delta H/\Delta z$ (m m^{-1}) was calculated as the change in total hydraulic head per unit distance between the two measurement depths:

$$\Delta H/\Delta z = \frac{H_L - H_U}{z_L - z_U} \quad [2]$$

where z is distance and ($z_L - z_U$) had a value of 0.305 m in this study.

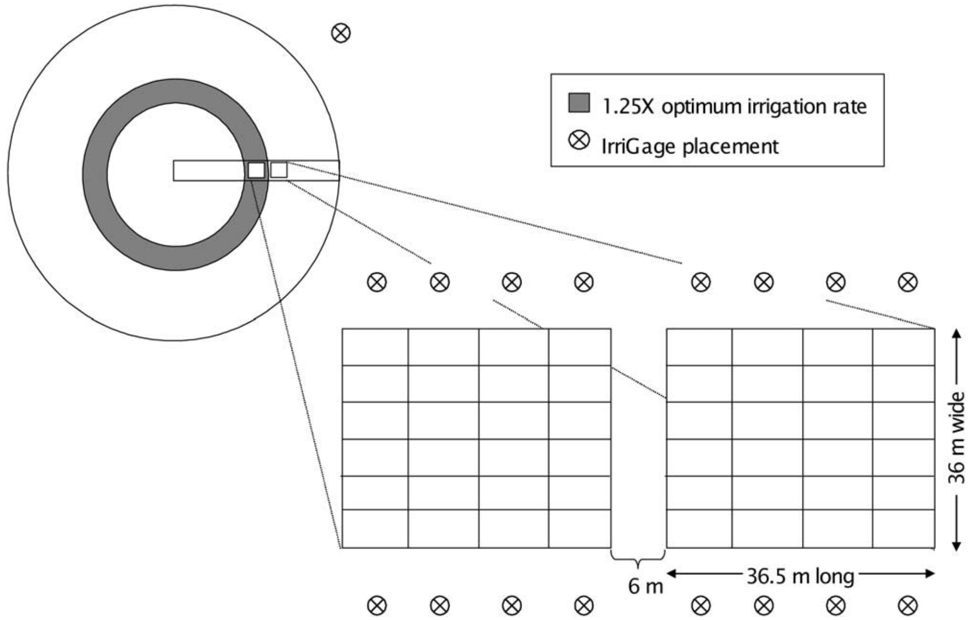

Fig. 2. Plot layout at the study site including IrriGage placement.

A cooperative study at the same site was conducted by Wetter (2004) to determine the hydraulic conductivity, $K(h)$, of the study soil and the relationship between $K(h)$ and h (following the approach by Vachaud and Dane, 2002), which was determined to be:

$$\mathrm{Log}_{10}K(h) = 3.318 - 36.441h^2 \quad [3]$$

where $K(h)$ is in mm d^{-1}, and h is in m of water and represents the mean matric potential ($n = 2$) for the 137- and 168-cm tensiometers. Equation [3] was used to determine $K(h)$ for each plot and each sampling event.

Water flux at each plot location was calculated using Darcy's equation of water flow (Vachaud and Dane, 2002):

$$q = -K(h)(\Delta H/\Delta z) \quad [4]$$

where q is the water flux in mm d^{-1}. To minimize apparent outliers, water flux values greater than 10 mm d^{-1} for an individual plot were set equal to 10 mm d^{-1} (occurrence of outliers was <5% of all values in 2001, <2% of all values in 2002). Because of differing time spans between water sampling events, an additional cap was set so that total drainage within a sample period did not exceed 75 mm (this cap was applied for <2.5% of all values in 2001 and 2002). The length of a sampling period did not exceed 12 d, with the exception of the 28-d sampling period from 27 Aug. to 24 Sept. 2002. Cap values were determined after review of the soil moisture release curve and hydraulic conductivity versus matric potential relationship determined by Wetter (2004) for this soil. Water flux in excess of 10 mm d^{-1} could not likely be sustained for an extended period, and maximum profile drainage until $K(h)$ is almost 0 (for the 152-cm profile) corresponds to 75 mm of water. Total water flux at the 152-cm depth for each irrigation treatment (q_l) was calculated as the product of mean daily water flux ($\overline{q}$) and the sampling time increment (Δt):

$$q_l = \overline{q} \times \Delta t \quad [5]$$

For a given sampling date, Δt was determined as the number of days between sampling dates, divided by two.

Daily NO_3 flux was calculated as the product of the NO_3–N concentration in the leachate sampled at 152 cm (for each plot) multiplied by the mean water flux ($n = 16$) for a given irrigation treatment on a given day:

$$N_q = C_{152} \times \overline{q} \quad [6]$$

where N_q is the mass of NO_3–N leached (kg N ha^{-1} d^{-1}), C_{152} is the NO_3–N concentration in kg N cm^{-1} ha^{-1}, and $\overline{q}$ is the mean water flux in cm d^{-1}. On days when tensiometer readings were recorded but soil water samples were not collected, the NO_3–N concentration was estimated using time-weighted interpolation of the NO_3–N concentration in soil water on the previous sampling date (C_a) and the subsequent sampling date (C_b) by using:

$$C_{152} = C_a + \left[\left(\frac{\text{days from } C_a \text{ to } C_{152}}{\text{days from } C_a \text{ to } C_b}\right) \times (C_b - C_a)\right] \quad [7]$$

The total mass of NO_3–N leached to below the root zone (N_l) for each N treatment within each irrigation treatment was calculated as the product of daily NO_3–N flux (N_q) and Δt:

$$N_l = N_q \times \Delta t \quad [8]$$

The seasonal total mass of NO_3–N leached for each N treatment within each irrigation treatment was calculated as the sum of N_l during May through September. A nitrogen mass balance was not completed because tissue and grain N analyses were not determined in this study.

Water inputs at the site were measured on the same schedule as tensiometer readings during 2001 and 2002. Precipitation (both natural and irrigation) was measured using non-evaporative precipitation collectors (IrriGages; Clark et al., 2002). Seventeen IrriGages were placed at the field site, 16 of which were located along the sides of the treatment blocks (about 5 m from the outer edge of the plots) (Fig. 2). The remaining IrriGage was placed at the corner of the field to measure rainfall (i.e., not exposed to irrigation). IrriGages were installed at a height of 1.5 m above the ground and all vegetation was removed from within a 2-m radius around each IrriGage.

Grain yield was determined by hand harvesting a 6-m length of each of the middle two rows from each plot. Corn was shelled with a spike cylinder sheller and then weighed, and yields were adjusted to 155 g kg^{-1} moisture content.

Statistical analyses were performed according to General Linear Procedures (SAS Institute, 1998). F tests for analyses of variances were considered significant at the 0.10 probability level. PROC GLM (SAS Institute, 1998) was used to analyze treatment differences in grain yield. Repeated measures analysis (SAS Institute, 1998) was used to evaluate time effects. In Eq. [5], mean water flux for each irrigation treatment was used after verification with PROC GLM (SAS Institute, 1998) that there was no significant difference in water flux among N treatments on a given sampling day, yet a difference was observed between irrigation treatments.

RESULTS AND DISCUSSION

Soil physical characteristics at this location were representative of the sandy soils along Kansas' main rivers. Dry bulk density determined in 30-cm increments is given in Table 1. Values ranged from 1.41 to 1.71 g cm^{-3} in the 0- to 240-cm soil profile, and are consistent with values previously determined for this soil type (Soil Survey Staff, 2004). Analysis of soil texture indicated that sandy-textured soil horizons were predominant in the 0- to 240-cm soil profile, with sand content of ≥0.87 g g^{-1} in all of the measured depths (Table 1).

Water samples collected from the irrigation system water supply in 2002 had a mean NO_3–N concentration of 6.1 mg L^{-1}, corresponding to total N inputs of about 14 and 17 kg N ha^{-1} for the 1.0× and 1.25× irrigation schedules (IS), respectively.

Maximum grain yield was achieved with a split application of 125 kg N ha^{-1} for the 1.0× IS in 2002 and for the 1.25× IS in 2001 and 2002 (Table 2). There was no statistical difference between mean yield for any N treatments greater than the control for 1.0× (2002) or 1.25× (2001, 2002), indicating that all of these treatments resulted in maximum yield. For the 1.0× IS in 2001, the 250 kg N ha^{-1} split treatment resulted in a

Table 1. Selected soil physical characteristics.

Depth	Bulk density	Soil texture		
		Sand	Clay	Silt
cm	g cm^{-3}	g g^{-1}		
0–30	1.41	0.93	0.03	0.04
30–60	1.54	0.92	0.05	0.03
60–90	1.67	0.90	0.07	0.03
90–120	1.67	0.89	0.08	0.03
120–150	1.60	0.90	0.09	0.01
150–180	1.66	0.90	0.08	0.02
180–210	1.67	0.87	0.10	0.03
210–240	1.71	0.88	0.09	0.03

greater yield than all other treatments except the 185 kg N ha^{-1} split treatment. No significant yield differences were observed between the irrigation treatments in either year. Regardless of irrigation treatment or year, a split application of 185 kg N ha^{-1} was sufficient to obtain maximum corn grain yield. This result is consistent with previous research indicating that similar corn grain yield can be obtained with lesser N rates when N is split-applied, compared with yield obtained with single greater rate N applications. Guillard et al. (1999) reported no difference in corn dry matter yield among N treatments that included a preplant application of 196 kg N ha^{-1} and split N applications totaling 135 kg N ha^{-1}. Rasse et al. (1999) showed similar corn grain yields among N treatments including a single preplant N application of 202 kg N ha^{-1} and split N applications totaling 101 kg N ha^{-1}. The increased recovery of N by the corn plant when N is split-applied is the major contributor to maintaining crop yields with reduced rates of N fertilizer (Herron et al., 1971; Gerwing et al., 1979; Bundy et al., 1994; Guillard et al., 1999). This increased recovery can be attributed to applying N just before the period of rapid N uptake by corn, resulting in a shorter time of exposure to leaching or denitrification risks (Bundy et al., 1994).

Maximum and minimum air temperatures were similar for both years (Table 3), with an average growing season maximum temperature of 30°C in each year and average minimum temperatures of 16.7 and 16.4°C for 2001 and 2002, respectively. The monthly average grass-reference evapotranspiration (ET_o) was also similar for both years, with a mean growing season value of 152 mm mo^{-1} for 2001 and 157 mm mo^{-1} for 2002. Rainfall in 2001 was 494 mm between May and September, and was greater than the 323 mm observed in 2002. These values (Table 3) are slightly different than those measured at the field site for several rainfall events, but are useful for this general comparison. Rainfall was less than the 30-yr mean for the county in all months except May and September of 2001 and August of 2002. Full season corn varieties grown in Kansas typically require 610 to 760 mm of precipitation for optimum production (Kansas State University, 1994), so supplemental irrigation was necessary to sustain yield in both study years. Cumulative precipitation (rainfall and irrigation) measured at the study site was greater in 2001 than in 2002, with a mean each year across both irrigation treatments of 586 and 464 mm, respectively (Fig. 3). In 2001, total precipitation for the 1.0× IS was 552 mm, with 251 mm applied as irrigation. The 1.25× IS had a total precipitation of 620 mm, with 319 mm applied as irrigation. Although rainfall totals and frequency were less in 2002, less irrigation was also applied in 2002 compared with that applied in 2001. Total precipitation for the 1.0× IS in 2002 was 437 mm, with 192 mm applied as irrigation, and the 1.25× IS had a total precipitation of 490 mm, with 245 mm applied as irrigation.

Table 2. Grain yield (adjusted to 155 g kg^{-1} moisture content) as a function of N treatment. Means labeled with the same letter for a given year are not different as determined by least significant difference (LSD) at α = 0.10.

	Irrigation treatment†			
	1.0×		1.25×	
Treatment	2001	2002	2001	2002
kg N ha^{-1}	Mg ha^{-1}			
0	2.7c	7.2b	3.5b	7.0b
125 split‡	9.1b	11.1a	11.2a	10.9a
185 split§	10.1ab	11.6a	11.3a	11.4a
250 split¶	11.1a	11.6a	12.0a	10.4a
250	9.3b	11.1a	12.7a	9.7a
300	9.0b	10.5a	11.9a	10.3a
Mean	8.5	10.5	10.4	10.0
$LSD_{0.10}$	1.2	1.3	1.5	2.0

† Irrigation treatments of 1.0× (recommended rate) and 1.25×.
‡ Split N application: 20% applied at planting, 40% at V6 crop stage, 40% at V10 crop stage.
§ Split N application: 33% applied at planting, 67% applied at V6 crop stage.
¶ Split N application: 50% applied at planting, 50% applied at V6 crop stage.

Table 3. Weather data for 2001 and 2002 collected about 23 km from the field site.

	Mean temperature				
Month	Maximum	Minimum	ET_o†	Rainfall	Deviation from mean‡
	°C		mm		
			2001		
May	24	12	124	150	46
June	29	17	157	65	−22
July	36	22	195	67	−14
August	34	19	176	33	−33
September	27	14	109	179	121
Mean	30	17	152	99	13
			2002		
May	24	11	129	40	−64
June	32	16	180	86	−2
July	34	20	187	55	−25
August	32	20	160	115	48
September	28	15	129	27	−30
Mean	30	16	157	52	−40

† Grass-reference crop evapotranspiration.
‡ Deviation (current year-average) from mean rainfall (1971–2000) for Stafford County, KS (Kansas State University, 2004).

Water Flux below the Root Zone

Water flux for the 1.25× IS was consistently the same or greater than water flux for the 1.0× IS in 2001 and 2002 (Fig. 4). No difference in water flux was detected among N treatments in either year.

Statistical differences in drainage between days (repeated measure in time) could not be determined because of missing points in the dataset, but noteworthy increases occurred three times during the 2001 growing season. Early in the 2001 growing season (30 May–12 June; Fig. 4), water flux increased after three rainfall events that exceeded 25 mm each (Fig. 3). A second notable increase occurred after 5 July, coinciding with an increased irrigation frequency and volume during a period when crop demand is generally high. An increase in water flux for the 1.25× IS at the end of the season (2001) was likely a result of rain in late August through mid-September, when crop demand had decreased as a result of crop maturation. The increase in water flux after 31 Aug. 2001 for the 1.25× IS, but not observed for the 1.0× IS, was likely a function of the greater soil profile moisture continually maintained in the 1.25×

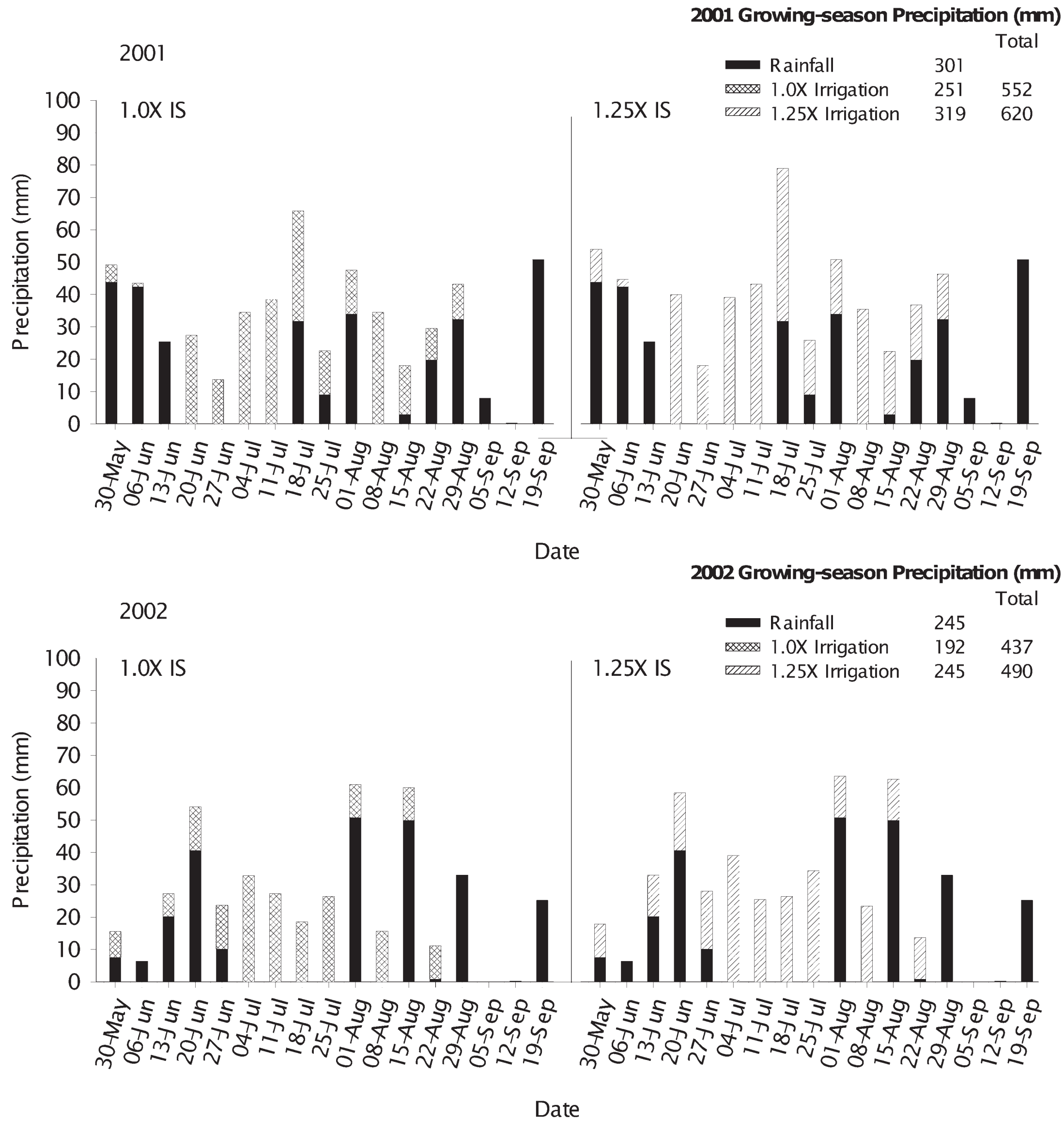

Fig. 3. Weekly summary of irrigation and rainfall data in 2001 and 2002. 1.0× IS = optimum irrigation; 1.25× IS = >25% optimum irrigation.

IS. With increased soil moisture, hydraulic conductivity increases resulting in greater drainage.

In 2002, a notable increase in water flux for the 1.25× IS occurred in mid-June (Fig. 4) after two large rainfall events on 13 and 20 June (Fig. 3). Another increase occurred during the third week in July. The increases in water flux were more pronounced for the 1.25× IS, corresponding to the wetter soil profile under that treatment.

Considering the variability inherent in field measurements of soil water flux using the tensiometric method, results here provided a reasonable approximation of water flux during each growing season. Water flux values determined using Eq. [5] are similar to those reported by Hergert (1986) for the 150-cm depth of a sandy soil in Nebraska under two irrigation schemes. Using a weekly water-balance approach based on neutron probe measurements, Hergert (1986) reported 52 mm of percolation for a 0.85 ET irrigation treatment compared with 165 mm for a 1.3 ET irrigation treatment over two study years. Mean rainfall plus irrigation values during the two years were 370 and 574 mm for the 0.85 ET and 1.3 ET irrigation treatments, respectively, compared with the 2-yr means of 494 and 555 mm for the 1.0× IS and 1.25× IS of our research. Relatively low flux values for the 1.0× IS were expected because this irrigation schedule was designed to provide only enough water to maximize crop growth and yield. Large increases in water flux could be expected when excessive irrigation occurs on these rapidly permeable sandy soils with low water holding capacities. Subtracting water flux values (tensiometric method) from the total growing season precipitation indicates that in 2001 about 519 and 444 mm of water were available for crop use in the 1.0× and 1.25× IS, respectively, compared with 426 and 374 mm in 2002 (ignoring runoff and evaporative losses). Our results indicate that excess irrigation by as little as 25% can dramatically increase water flux in these sandy soils (by as much as 10×).

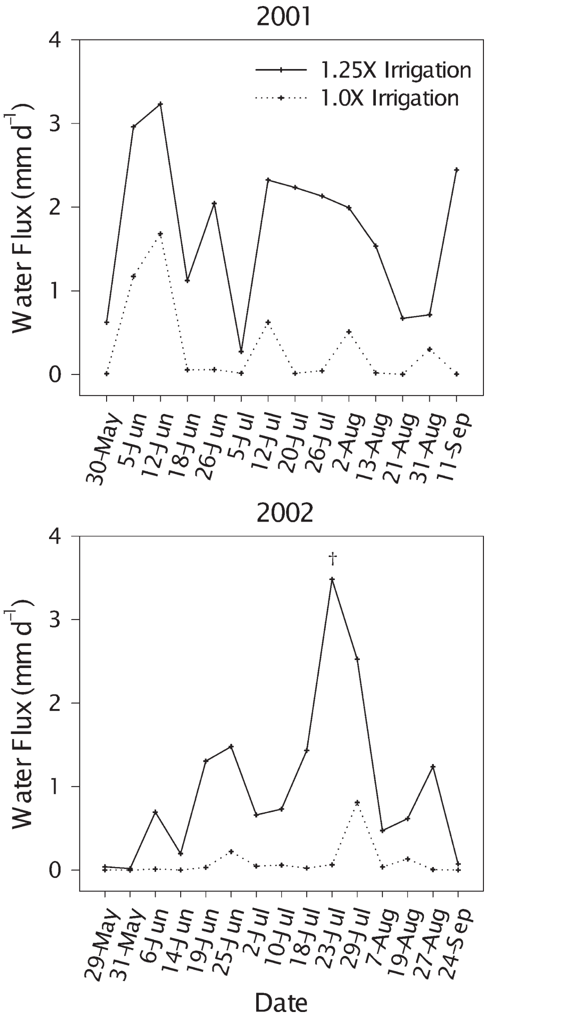

Fig. 4. Water flux determined at the 152-cm depth for two irrigation schedules (recommended rate and 25% over recommended rate) during the 2001 and 2002 growing seasons. On a given sampling date, † indicates a significant difference in water flux between irrigation treatments (Prob. > F = 0.10).

Soil Water Nitrogen Concentrations

Soil water samples were collected for analysis of NO_3–N and NH_4–N on six dates in 2001 and nine dates in 2002. Concentrations of NH_4–N in soil solution were very low (<1 mg L^{-1}) during most of the sampling events (>96% of sampling events), consistent with results from previous research by Paramasivam et al. (2001) and Hergert (1986). Average NH_4–N concentration for the two irrigation schedules across all N treatments and both years was the same, 0.15 mg L^{-1} for both the 1.0× and 1.25× IS. The mean soil water NO_3–N concentration for the two irrigation schedules, averaged across N treatments and years, was 53 mg L^{-1} for the 1.0× IS and 66 mg L^{-1} for the 1.25× IS. Accordingly, NO_3–N concentrations in soil solution were used to estimate N leaching losses.

Preseason soil samples provided a check for NO_3–N concentrations determined in soil water at the beginning of the season. Averaged across all N treatments and both water treatments, the mean preseason soil NO_3–N concentration between 120 and 180 cm was 4.3 mg kg^{-1} in 2001 and 2.6 mg kg^{-1} in 2002. Mean NO_3–N concentrations in soil water [corrected for water content by volume (θ) and dry bulk density] determined on the first water sampling (152-cm depth) dates in 2001 and 2002 were 6.3 and 2.9 mg kg^{-1}, respectively. The similarity in NO_3–N concentration between these two methods suggests that point estimates from water samples reasonably represent the inorganic soil N status at the site.

The pattern of soil water NO_3–N concentration at the 152-cm depth during the growing season was similar for both study years, with concentrations greater toward the end of the growing season for all N treatments (Fig. 5). The relatively low concentrations at the beginning of the season suggest that little of the previous year's applied N carried over to the following spring as inorganic N. This trend is inconsistent with the seasonal leaching pattern observed for irrigated Valentine fine sand soils in Nebraska by Hergert (1986), who showed increased concentrations early in the growing season, representing breakthrough of the previous year's N application. In a study on irrigated Eudora loam soils in Kansas, Heitman (2003) reported a leaching pattern similar to that observed by Hergert, although increased concentrations that were attributed to breakthrough from the previous year did not occur until later in the growing season (late July).

Early in the growing season, soil water NO_3–N concentrations ranged among N treatments from 36 to 64 mg L^{-1} in 2001 and from 14 to 39 mg L^{-1} in 2002 (Fig. 5A and 5B). As early as 26 June 2001, however, there were significant differences in NO_3–N concentration among N treatments. Differences among N treatments in 2001 were also observed on 12 July, 26 July, and 31 August. Although main effects of N treatment were not observed in 2002 (Fig. 5B), reflecting the variability inherent to this type of research, trends throughout the growing season were similar between years. By late July in both years, NO_3–N concentrations were exceeding 100 mg L^{-1} for the single preplant applications. A significant N treatment by time interaction was observed between 19 Aug. and 24 Sept. 2002. Nitrate concentration between these dates decreased for all treatments except the 250 kg N ha^{-1} split application, which increased slightly, and the 250 kg N ha^{-1} single application decreased more compared with the changes observed for the other N treatments.

Nitrate concentration for the 1.25× IS was consistently greater than that observed for the 1.0× IS in 2001, with a significant difference between the treatments observed on four sampling dates (Fig. 5C). A significant interaction between time and irrigation treatment was observed between 12 July and 26 July and between 13 and 31 Aug. 2001. The first interaction reflects the slight increase in NO_3–N concentration for the 1.0× IS compared with the more pronounced increase for the 1.25× IS. The second interaction was due to an increase in NO_3–N concentration for the 1.25× IS compared with a decrease for the 1.0× IS in the same time period.

In 2002, the 1.0× IS had significantly higher NO_3–N concentrations than the 1.25× IS on 29 May and 24

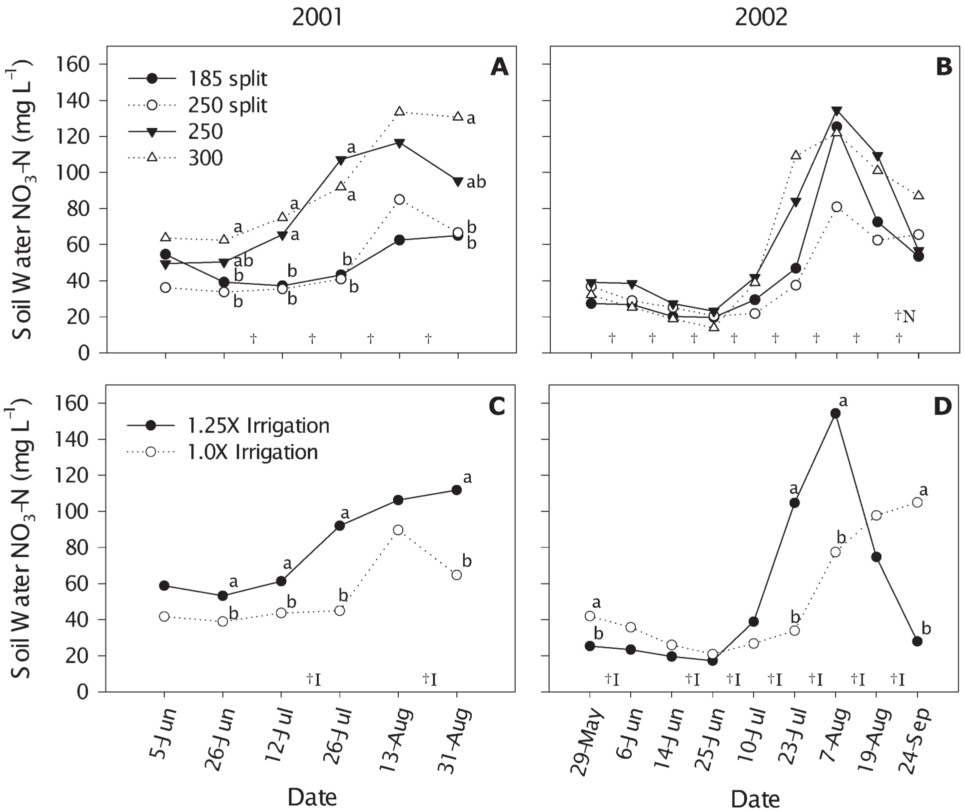

Fig. 5. Mean soil water NO_3–N concentrations (152-cm depth) throughout the growing season for (A, B) several N (kg N ha^{-1}) treatments and (C, D) two irrigation treatments. Means labeled with the same letter on a given date are not different as determined by LSD at $\alpha = 0.10$. Significant differences in NO_3–N from one sampling date to the next are indicated with a †, N treatment by time interactions with a †N, and irrigation treatment by time interactions with a †I, as determined by repeated measures analysis at $\alpha = 0.10$.

September (Fig. 5D), and significant time by irrigation treatment interactions were observed between all sampling dates except for the 6 to 14 June time increment. The greater NO_3 concentration observed with the 1.0× IS on 29 May could be attributed to remnant N from the previous growing season (similar to that observed by Hergert, 1986), because more NO_3 was leached in 2001 from the 1.25× IS (see later discussion). The relatively rapid increase in NO_3–N concentration for the 1.25× IS (compared with the 1.0× IS) between 10 July and 7 August suggests that a large downward flux of NO_3 to and below the 152-cm depth may have occurred during this time, reducing the NO_3 remaining in the soil water at the 152-cm depth after 7 August. Increasing soil water NO_3–N concentrations at the 152-cm depth as a result of additional water and single preplant N applications translates to greater NO_3 leaching potential during the growing season. The increase in NO_3–N concentration that was still occurring at the end of the 2002 growing season (for the 1.0× IS) is an indication that N applied in excess of that needed for optimum crop growth can result in high soil water NO_3–N concentrations and pose a leaching risk after the growing season.

Similar to the results of our study, an increase in soil water NO_3 concentration after July was reported by Heitman (2003), although he attributed this increase to a breakthrough from the previous year's management. In addition, he found similar NO_3 concentrations for single preplant application and split N treatments until mid growing season, when NO_3 concentrations under preplant applications became greater than that for split applications after a period of overall NO_3 concentration decline. A possible explanation for these late-season differences was a decrease in "excess" NO_3 available for leaching from the split N application. Hergert (1986) showed a general increase in NO_3 concentration after late July for an irrigation treatment that exceeded crop ET (1.3 ET), and seasonal NO_3 concentration was generally greater for this irrigation treatment compared with a 0.85 ET treatment. Although data were inconsistent for individual years, the studies by Hergert (1986) and Heitman (2003) also showed decreases in soil water NO_3–N concentration at the end of the growing season. Unlike the results of these previous studies, results from our research did not indicate a carryover of soil water NO_3–N from the end of one growing season to the beginning of the next growing season, except for the 1.0× IS in the spring 2002 (Fig. 5D). The declining NO_3–N concentration observed at the end of each growing season is indicative that NO_3 in the soil matrix was moving down the profile before harvest. Nitrate N concentration was greater in the 1.25× IS than the 1.0× IS at the end of the growing season (Fig. 5C), but smaller with the 1.25× IS in the spring of 2002 (Fig. 5D), suggesting that NO_3 in the 1.25× IS was moving more rapidly through the soil profile during the growing season and then leached below the 152-cm depth before spring. Characteristics of the soil at this site (i.e., rapid permeability)

Table 4. Leaching losses of NO_3–N on each sampling date for the 2001 growing season. Means labeled with the same letter for a given date are not different as determined by least significant difference (LSD) at $\alpha = 0.10$.

	Date													
	30 May	5 June	12 June	18 June	26 June	5 July	12 July	20 July	26 July	2 August	13 August	21 August	31 August	11 September
	kg NO_3–N ha^{-1} d^{-1}													
N treatment, kg N ha^{-1}														
185 split†	0.158	0.962	1.084b	0.269b	0.457bc	0.061b	0.594b	0.532b	0.551	0.621b	0.369	0.179	0.320b	0.738c
250 split‡	0.123	0.783	0.897b	0.213b	0.365c	0.051b	0.525b	0.457b	0.480	0.702b	0.629	0.274	0.368b	0.997bc
250	0.192	1.190	1.351ab	0.343ab	0.604ab	0.095a	1.024a	1.232a	1.455	1.436a	0.912	0.390	0.471b	1.387b
300	0.250	1.531	1.736a	0.441a	0.767a	0.115a	1.212a	1.213a	1.331	1.529a	1.192	0.540	0.740a	2.059a
Mean	0.181	1.116	1.267	0.316	0.548	0.081	0.839	0.858	0.954	1.072	0.776	0.346	0.475	1.295
$LSD_{0.10}$	NS§	NS	0.554	0.143	0.235	0.038	0.387	0.571	NS	0.556	NS	NS	0.219	0.655
Irrigation treatment¶														
1.0×	0.005b	0.543b	0.737b	0.024b	0.023b	0.007b	0.272b	0.007b	0.021b	0.305b	0.017b	0.003b	0.195b	0.005b
1.25×	0.356a	1.690a	1.796a	0.609a	1.072a	0.155a	1.406a	1.710a	1.888a	1.839a	1.534a	0.688a	0.754a	2.586a
$LSD_{0.10}$	0.067	0.400	0.385	0.100	0.165	0.025	0.267	0.400	0.585	0.389	0.537	0.178	0.152	0.455

† Split N application: 33% applied at planting, 67% applied at V6 crop stage.
‡ Split N application: 50% applied at planting, 50% applied at V6 crop stage.
§ Nonsignificant at the 0.10 probability level.
¶ Irrigation treatments of 1.0× (recommended rate) and 1.25×.

suggest that, even with limited precipitation in the over winter period, any remaining NO_3 observed in the soil profile at the end of the growing season (2001) probably moved to below the sampling depth before the 2002 growing season.

Nitrate Leaching Losses

Total NO_3–N leaching losses were determined for individual plots using soil water NO_3–N concentrations observed for each plot with mean soil water drainage for each irrigation treatment. Nitrate leaching was greater for the 1.25× IS than for the 1.0× IS on all sampling dates in both years (Tables 4 and 5). The mean daily rates of NO_3–N flux for all sampling dates in 2001 were 0.2 (1.0× IS) and 1.3 kg ha^{-1} d^{-1} (1.25× IS). Lower seasonal water flux and lower soil water NO_3–N concentration in 2002 resulted in lower daily NO_3–N flux in 2002 compared with that in 2001, with mean daily rates of 0.1 (1.0× IS) and 0.7 kg ha^{-1} d^{-1} (1.25× IS). Maximum NO_3 leaching within an irrigation treatment occurred on 11 Sept. 2001 (2.586 kg N ha^{-1} d^{-1}) and on 23 July 2002 (3.645 kg N ha^{-1} d^{-1}), corresponding to the period of increased water flux (Fig. 4) and increased soil water NO_3–N concentrations (Fig. 5).

Significant differences in NO_3 leached among N treatments were observed on 9 of 14 sampling dates in 2001 (Table 4) and 2 of 15 sampling dates in 2002 (Table 5). On all of these dates, the 300 kg N ha^{-1} treatment resulted in a greater amount of NO_3 leached than did either of the split N applications. Although leaching losses were generally the same for the 300 and 250 kg N ha^{-1} single applications, the 300 kg N ha^{-1} treatment resulted in greater NO_3 leaching on the last two sampling dates in 2001. The mean daily NO_3 losses in 2001 were 1.0, 0.9, 0.5, and 0.5 kg N ha^{-1} d^{-1} for the 300, 250, 250 split, and 185 split kg N ha^{-1} treatments, respectively. In 2002, corresponding NO_3 leaching losses were 0.5, 0.5, 0.3, and 0.3 kg N ha^{-1} d^{-1}.

The summation of daily NO_3 losses provides an estimate of the growing season total NO_3 loss to below the 152-cm depth. Data from both years indicate the effectiveness of irrigation management on reducing growing season NO_3 leaching losses, with a relatively small mean loss (across all N treatments) from the 1.0× IS of 16 kg N ha^{-1} in 2001 and 6 kg N ha^{-1} in 2002 (Fig. 6). A rather dramatic increase in leaching was observed for the 1.25× IS, with as great as a 16-fold increase over the 1.0× IS for some N treatments. Across all N treatments, mean NO_3 leaching losses for the 1.25× IS were 133 kg N ha^{-1} in 2001 and 86 kg N ha^{-1} in 2002. These data

Table 5. Leaching losses of NO_3–N on each sampling date for the 2002 growing season. Means labeled with the same letter for a given date are not different as determined by least significant difference (LSD) at $\alpha = 0.10$.

	Date														
	29 May	31 May	6 June	14 June	19 June	25 June	2 July	10 July	18 July	23 July	29 July	7 August	19 August	27 August	24 September
	kg NO_3–N ha^{-1} d^{-1}														
N treatment, kg N ha^{-1}															
185 split†	0.005	0.002	0.079	0.021	0.147	0.187	0.084	0.102	0.266	0.791b	1.439b	0.414	0.237	0.314	0.010
250 split‡	0.005	0.002	0.059	0.013	0.084	0.115	0.051	0.067	0.251	0.842b	1.103b	0.293	0.235	0.353	0.014
250	0.007	0.003	0.111	0.022	0.133	0.154	0.112	0.195	0.702	2.286ab	2.180a	0.484	0.430	0.608	0.013
300	0.006	0.003	0.085	0.019	0.124	0.142	0.127	0.236	1.008	3.414a	2.389a	0.337	0.284	0.323	0.008
Mean	0.006	0.002	0.084	0.019	0.122	0.149	0.094	0.150	0.557	1.833	1.777	0.382	0.297	0.400	0.011
$LSD_{0.10}$	NS§	NS	NS	NS	NS	NS	NS	NS	NS	1.982	0.725	NS	NS	NS	NS
Irrigation treatment¶															
1.0×	0.001b	0.000b	0.005b	0.001b	0.007b	0.045b	0.011b	0.015b	0.007b	0.021b	0.406b	0.030b	0.132b	0.007b	0.001b
1.25×	0.010a	0.005a	0.162a	0.037a	0.237a	0.254a	0.176a	0.285a	1.107a	3.645a	3.149a	0.734a	0.462a	0.793a	0.021a
$LSD_{0.10}$	0.002	0.001	0.039	0.012	0.075	0.086	0.059	0.119	0.431	1.400	0.513	0.114	0.173	0.204	0.007

† Split N application: 33% applied at planting, 67% applied at V6 crop stage.
‡ Split N application: 50% applied at planting, 50% applied at V6 crop stage.
§ Nonsignificant at the 0.10 probability level.
¶ Irrigation treatments of 1.0× (recommended rate) and 1.25×.

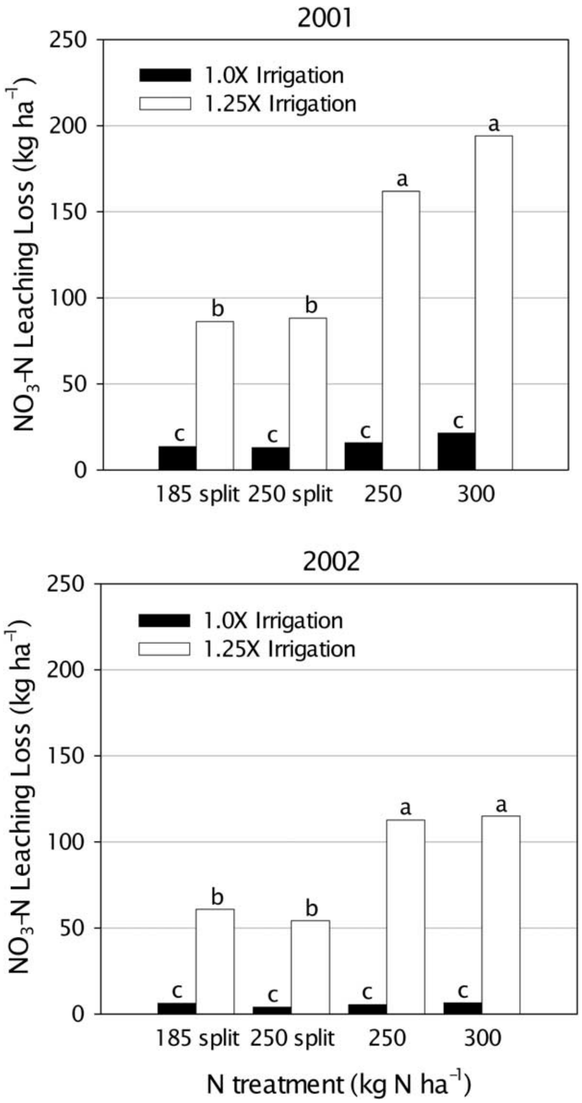

Fig. 6. Seasonal leaching losses of NO_3–N for four N treatments and two water treatments in 2001 and 2002. Bars labeled with the same letter for a given year are not different as determined by LSD at $\alpha = 0.10$.

are similar to results observed by Hergert (1986), who reported mean NO_3 leaching losses during two growing seasons of 61 kg ha^{-1} for a 0.85 ET irrigation schedule and 148 kg ha^{-1} for a 1.3 ET irrigation schedule.

No significant differences in seasonal total N leaching were observed among N treatments for the 1.0× IS in either year, but results from the 1.25× IS demonstrate the increased importance of N management when irrigation exceeds the optimum rate by as little as 25%. Mean NO_3 leaching losses for the 1.25× IS across both years were nearly twice as great for the single preplant applications than for the split N applications, with NO_3 losses of 146 and 72 kg N ha^{-1}, respectively (Fig. 6). In 2001, leaching losses for the split N application averaged 87 kg N ha^{-1} compared with 178 kg N ha^{-1} for the single preplant applications. Growing season leaching losses were somewhat less in 2002, although losses from the split N applications (58 kg N ha^{-1}) were significantly less than that from the single N applications (114 kg N ha^{-1}). These results illustrate that even if N is applied using sound management practices (e.g., split applications), NO_3 leaching can be substantial if sandy soils are excessively irrigated.

CONCLUSIONS

Application of N fertilizer and irrigation water to meet but not exceed crop requirements is important to reducing the NO_3 leaching from irrigated sandy soils. The NO_3 leaching potential of a soil is influenced primarily by water flux down the soil profile and NO_3 concentration in the soil matrix. Management decisions that increase downward water flux, especially at times when soil NO_3 concentration is high, enhance the risk of loss of NO_3 to below the crop root zone. Results from this study indicate that irrigation in excess of that required to replenish crop water use (1.25× IS) did not enhance corn yield, and maximum grain yield was achieved with a split-applied fertilizer rate of 185 kg N ha^{-1} or less. Differences in growing season soil water flux and NO_3 leaching among N and water treatments emphasize the importance of irrigation scheduling and N management to minimize the potential for NO_3 leaching.

Soil water NO_3 concentration increased in the latter half of each growing season and was generally greater in plots that received the 1.25× IS and single preplant N applications, compared with that in plots receiving split N applications or the 1.0× IS (Fig. 5). Seasonal leaching losses were substantially greater for the 1.25× IS and single preplant N applications, with losses of nearly 200 kg N ha^{-1} for the 300 kg N ha^{-1} application in 2001. Lower seasonal precipitation resulted in less soil water flux and less leaching losses in 2002; although total NO_3 leached for the single preplant N rates and 1.25× IS remained in excess of 100 kg N ha^{-1}. One conclusion from this study might be that greater irrigation rates could possibly translate to greater N fertilizer requirements, because rapid percolation would occur with excessive water inputs (thus leaching N down the profile). However, even for the 1.25× IS, corn yield was not significantly increased with N fertilizer in excess of 125 kg N ha^{-1}. Perhaps greater N mineralization under the 1.25× IS compensated for N lost due to leaching.

Efficient irrigation management is important to minimizing NO_3 leaching in irrigated corn, especially when N fertilizer is applied in excess of that required by the crop. However, careful irrigation management alone will not prevent NO_3 loss when poor N management decisions are made, because N applied in excess of crop requirements and remaining in the soil after the growing season will be susceptible to leaching during the winter fallow period. Split N applications can reduce the quantity of N in the soil, especially early in the growing season, and minimize the environmental risks associated with periods of high water input and low crop demand for water and N. Nitrate contamination of ground water will only be minimized by managing both irrigation and N to meet crop needs.

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